

The Calculation of Control Rod Worth

by

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Over the years control rod reactivities have been calculated using many different methods and cross section sets.

The most widely used calculational techniques were:

two-dimensional diffusion in RZ geometry for central control rods and varying insertion depths

two-dimensional diffusion in XY geometry for central and excentrical control rods fully withdrawn or fully inserted three-dimensional XY/Z diffusion synthesis (program KASY /1/) for all types of control rod experiments

two-dimaensional RZ transport for central rods in particular when large follower channels are involved

Monte-Carlo calculations (program MOCA /2/) for complicated multi-rod configurations.

The cross section sets used were NAPPMB /3/, MOXTOT /4/ and KFKINR /5/. They all belong to the same series of 26-group-sets; an improved version is prepared every few years.

The use of such diversified methods of calculation makes a systematical comparison with experiments somewhat difficult.

In the Table 1 a survey over results from all the SNEAK control rod experiments is given. One notes that for most experiments KASY synthesis results exist and that the MOXTOT cross section set was used over the whole series either as the main set or at least for additional test calculations. Thus a basis is provided for an overall comparison. Results with other cross

sections and with other calculational techniques are also given in order to complete the information and to show the influence of changing data and methods for a number of cases.

Not included in the table are the developments which have taken place in recent years in the determination of the delayed neutron fraction β_{eff} . These developments have two aspects:

1. A reevaluation of measurements of delayed neutron yields by Tuttle /6/ indicates that with the data by Keepin /7/ which have been used up to now these yields have been overestimated for the various fissionable isotopes, and that β_{eff} has to be increased from 4 % (for small U-235 cores) to 8 % (for large Pu-cores). Recent measurements of β_{eff} in SNEAK /8/ also agree with these changes.
2. Direct measurements of delayed neutron fractions (which usually were performed in hard spectrum assemblies) yield the amount of delayed neutrons per fission. When transferring the result to an assembly with a softer spectrum one has to keep in mind that not β itself (delayed neutrons per fission neutron) but $\nu\beta$ (delayed neutrons per fission) remains fairly constant, while β increases by about the same factor as ν decreases. If the evaluation is based on constant β as was the case up to now one introduces an error of 1 - 2 % for Pu-cores and of up to 4 % for uranium cores.

These facts have not been included in Table 1 since consistent recalculations of all the assemblies have not yet been performed. However, the data mentioned here allow an estimate that for all the assemblies considered in this evaluation the β_{eff} would increase by about 8 %, leading to a decrease of the C/E values by about the same amount.

The evaluation of the experiments has shown that, for diffusion calculations, the differences between measurements and calculations are strongly influenced when follower material (low transport cross sections) is put in or out of the reactor.

The experiments have therefore been divided into the three categories: fuel replaced by follower, first insertion steps of absorber and complete insertion of absorber. Within each of these groups the diffusion results agree with a scatter of about 10 %.

Table 4 Comparison of calculated and measured control rod worths for B₄C rods

Case	Core height	Measurement method	Reactivity measured (ΔK/K, %)	Calculations (C/E) ^{a)}			Transport Calc.
				NAPPMB	MOXTOT	KFKINR	
Fuel replaced by tellower material							
2C, central rod	60	quasier.	0.506	1.24	1.25 ^{c)}		S4, RZ, NAPPMB 0.94
2C, excentrical rod	60	"	0.434	1.07	1.08 ^{c)}		
6A, central rod	90	"	0.770	1.11 (RZ)	1.12 ^{c)}		S4, RZ, NAPPMB 1.03
6D, central rod	90	"	0.807	1.12 (RZ)	1.11		
9A-0, central rod /13/	90	"	0.596			1.50 (RZ)	S6, RZ, KFKINR 1.00
First insertion step of absorber into tellower							
2C, central rod 30 cm	60	quasier.	1.021	0.85	0.88 ^{c)}		
2C, excentrical rod 30 cm	60	"	0.424	0.95	0.99 ^{c)}		
6A, central rod 22.5 cm	90	mixed ^{b)}	0.67	0.87 (RZ)	0.91 ^{c)}		
9A-1 RT1 bank 15 cm	90	Source M.	0.464		0.91	0.87	
Complete insertion of absorber into tellower							
2C, central rod	60	quasier.	1.765	0.92	0.95 ^{c)}		
2C, excentrical rod	60	"	0.817	0.98	1.02 ^{c)}		
6A, central rod	90	mixed ^{b)}	2.91	1.02 (RZ)	1.05 ^{c)}		S4, RZ, NAPPMB 0.98
6D, central rod	90	mixed ^{b)}	3.12	1.02 (RZ)	1.03		
9A-1, RT1 bank	90	Source M.	3.89		0.99	0.94	MOCA, KFKINR
9A-2, RT1 + RT2 banks 40 to 90 cm	90	"	4.54		0.97	0.91	0.87 ± 0.06
9A-2, all rods 40 to 90 cm	90	"	7.55		0.96	0.90	0.87 ± 0.04

a) KASY XY/Z calculations except when stated otherwise

b) Measured in several steps, partly by rod compensation and partly by source multiplication

c) result extrapolated from the difference NAPPMB-MOXTOT in one-dimensional calculations for a central rod in SNEAK 2C

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In the cases where transport calculations are available one can see that they appear to eliminate the influence of the follower channels. This can be seen from Table 2, which is taken from ref. /8/, where the validity of diffusion theory was checked by S_4 calculations for a central Na-B₄C rod in SNEAK-6A. For the reactivity of the absorber B₄C, the one- and two-dimensional transport effects compare well. For the Na follower they differ largely: only in two-dimensions the advantage of transport in correctly describing the axial leakage of neutrons becomes effective.

The use of transport instead of diffusion always results in an improvement of the C/E ratios. But one must observe that for the case of sodium follower a geometrical model which contains the axial direction (i.e. 2D in this case and 3D in the general case) allows a definite conclusion on the transport correction

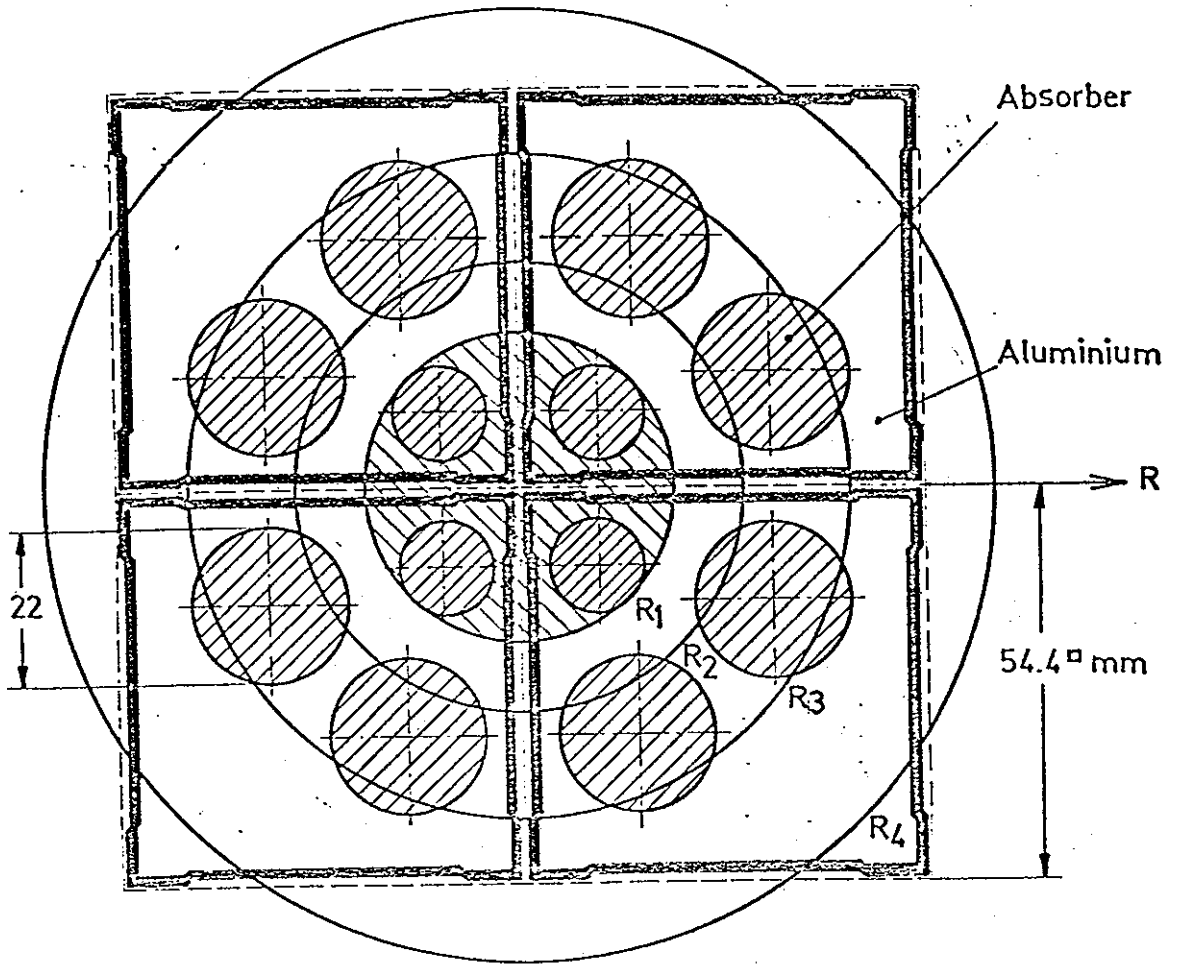
Table 2: Compared transport and diffusion results Reactivity of a central (Na-B₄C) rod in SNEAK-6A

Relative deviations (T-D)/D in % for the changes:	1D (R)	2D (RZ)
fuel-sodium	-1.8	-8.6
fuel-B ₄ C	-3.5	-5.0

It should be noted that in these evaluations no heterogeneity corrections have been applied. However, this correction is felt to be small.

Recent measurements on the absorber worth of Ta, B₄C, B₄C (90 % enriched) and Eu₂O₃ were performed in SNEAK 9C/2. Among others one aim was to measure the resonance selfshielding of Eu₂O₃. The reactivity worth was measured by positioning of trim rods.

All calculations have been performed in RZ-geometry with the 26 group set KFK-LNR in diffusion theory. One dimensional S_8 and XY corrections have been added to the RZ-results. According to Fig.1 the absorber rods were homogenized with the surrounding Al and steel.



- $R_1 = 1.85 \text{ cm}$
- $R_2 = 3.6 \text{ cm}$
- $R_3 = 4.8 \text{ cm}$
- $R_4 = 6.14 \text{ cm}$

Fig. 1: Representation of Control Rod Measurements

Table 3 compares the measured results with theoretical predictions. It can be seen that Ta gives the best agreement, for enriched boron and Eu_2O_3 the agreement is less satisfactory. The values for enriched boron seem to be uncertain because of the geometrical representation of the relativ short rods; the transport-correction for this case is about 10 %. One may also see from Part 2 of the table that the discrepancy between calculation and experiment increases with increasing Eu-mass.

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a) b)

Table 3: Results of Absorber Measurements in SNEAK 9C2 and 9C2/C

Part 1 Different Absorbers and Configurations

Absorber Type	B_4C		Ta		Eu_2O_3		B_4C enr. d) 20 square rods	1 square rod
	4 small rods +8 large ^{c)} rods	1 small rod	4 small rods +8 large rods	1 small rod	4 small rods +8 large rods	1 small rod		
Mass [B]	554.8	20.69	5963.6	218.7	2035.2	71.99	512.0	25.6
Measured worth [¢]								
9C2	-159.69		-137.32		-183.19		-304.48	
9C2/C	-152.93	-6.12	-133.81	-6.06	-174.51	-7.53	-289.47	-19.51
$\rho(\text{¢})/\text{g}(\text{Meas.})$								
9C2	0.2878		0.0230		0.0900		0.5947	
9C2/C	0.2756	0.2958	0.0224	0.0277	0.0857	0.1046	0.5654	0.7261
Calc./Meas.								
9C2	0.92		0.97		0.75		0.75	
9C2/C	0.90	0.96	0.95	0.97	0.72	0.82	0.71	0.74

Part 2 Single Eu_2O_3 -rods of different thicknesses in SNEAK 9C2

Rod diameter (mm)	30.5	21.8	12.6	6.6
weight (g)	461.62	210.41	71.99	18.17
Measured worth(¢)	-45.91	-23.16	-8.40	-2.25
$\rho(\text{¢})/\text{g}(\text{Meas.})$	0.0994	0.1101	0.1167	0.1238
Calc./Meas.	0.73	0.76	0.83	0.83

- a) PuO_2UO_2 fuel + Na
- b) Pu-metal fuel + graphite (carbide simulation) + Na
- c) small ~ 13 mm diameter, large ~ 22 mm diameter
- d) arrangement of square rodlets yielding a similar geometry as shown in Fig. 1

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